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AN ACCURATE NUMERICAL TECHNIQUE FOR DETERMINING FLIGHT TEST RATE GYROSCOPE BIASES PRIOR TO TAKEOFF

by

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National Aeronautical Establishment

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AN ACCURATE NUMERICAL TECHNIQUE FOR DETERMINING FLIGHT TEST RATE GYROSCOPE BIASES PRIOR TO TAKEOFF

TECHNIQUE NUMÉRIQUE PRÉCISE POUR DETERMINER LES ERREURS SYSTÉMATIQUES DES GYROMÈTRES D'ESSAI EN VOL AVANT LE DÉCOLLAGE

by/par

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National Aeronautical Establishment

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SUMMARY

Rate gyroscope biases play an important role in flight tests requiring flight path reconstruction, a method often used in aircraft parameter estimation. The biases can drift with time, be affected by system power up and, ideally, should be calibrated before each flight to maintain optimum performance. This report details a numerical method to determine the biases of high quality flight test rate gyroscopes immediately prior to a flight. The accuracy of the method is such that the earth rate is clearly sensed and accounted for, a variable rarely considered in flight testing. The method requires minimal time and no calibration hardware.

RÉSUMÉ

Les erreurs systématiques des gyromètres ont une grande influence dans les essais en vol qui nécessitent la reconstitution d'une trajectoire de vol, méthode souvent utilisée pour l'estimation des paramètres d'un aéronef. Les erreurs systématiques peuvent varier avec le temps et peuvent être influencées par la mise en marche de l'alimentation du système; c'est pourquoi, idéalement, les gyromètres devraient être étalonnés avant chaque vol afin qu'ils puissent offrir des performances optimales. Le présent rapport décrit une méthode numérique pour déterminer les erreurs systématiques des gyromètres de précision immédiatement avant le vol. La précision de cette méthode est telle, que le taux de précession apparente de la terre est clairement détecté, et que cette variable est prise en compte dans les calculs, ce qui est rarement le cas pour les essais en vol. La méthode n'exige que peu de temps, et ne fait appel à aucun instrument d'étalonnage.

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NOMENCLATURE

Symbol	Definition
a_{x_o}	initial x-accelerometer measurement (average)
a_{y_o}	initial y-accelerometer measurement (average)
a_{z_o}	initial z-accelerometer measurement (average)
b_p	roll rate gyro bias
b_q	pitch rate gyro bias
b_r	yaw rate gyro bias
L	geocentric latitude, positive in northern hemisphere
p	true angular velocity component in roll (positive direction is right-wing down)
q	true angular velocity component in pitch (positive direction is nose up)
r	true angular velocity component in yaw (positive direction is nose to the right)
p_m	measured angular velocity component in roll
q_m	measured angular velocity component in pitch
r_m	measured angular velocity component in yaw
θ	pitch angle (positive nose up)
ϕ	roll angle (positive right wing down)
ψ	yaw angle (see figure 2 for reference system)
Ω_e	Earth's rotation rate relative to inertial space
λ	geocentric longitude

AN ACCURATE NUMERICAL TECHNIQUE FOR DETERMINING FLIGHT TEST RATE GYROSCOPE BIASES PRIOR TO TAKEOFF

1.0 INTRODUCTION

In the context of flight testing, flight path reconstruction refers to integration of the inertial measurements over the brief time period of the manoeuvre, generating time histories of aircraft attitude and velocity components. The typical length of a manoeuvre is approximately 1 minute or less, hence the requirements for measurement accuracy are substantially less than that for inertial navigation where integration times of more than 1 hour are often required (with measurements being augmented by sophisticated Kalman filter integrated navigation algorithms to eliminate dominant errors). The flight path reconstruction results are, nonetheless, significantly affected by the instrument biases, and considerable effort is often spent in determining their value.

The University of Toronto Institute for Aerospace Studies flight test data acquisition system was obtained and used in this investigation. The temperature controlled inertial module contains 3 Honeywell GG1111AN02 rate gyroscopes and 3 Sundstrand QA-2000 Q-Flex accelerometers. This is considered very high quality flight test instrumentation.

To maintain peak performance, these instruments should be routinely calibrated to identify drift with time. Although impractical, they should be calibrated after each turn-on (before each flight) to establish the turn-on to turn-on bias shift. Furthermore, many data acquisition systems contain analogue to digital converters that are subject to bias drift with time, which may be interpreted as an instrument bias.

This report addresses a practical and accurate method of determining rate gyroscope biases prior to each flight.

2.0 TEST PROCEDURE

Although the following technique discusses the setup within the laboratory, it can easily be extended to include implementation within the aircraft prior to flight. The main assumptions are that the principal error sources are biases, and that they remain constant for the duration of the experiment (≈ 90 seconds).

The technique requires an inertial module capable of being rotated in all directions, and has the following simple steps:

1) Place the inertial module on any statiorary surface.

2) Begin recording data.

3) Manually rotate the inertial module about each of the three axes in both the positive and negative directions. Care must be taken so as not to overrange the instruments. See sample time histories of figure 1.

4) Return the inertial module to the starting location (exactly).

5) Stop recording data.

The idea is to select, via a searching algorithm, the gyro biases required to compensate for the differences between indicated values of the starting and ending angles of pitch, roll and yaw are zero. The search algorithm can, of course, be executed post-flight since this is typically when all data analysis is conducted. Knowledge of the initial pitch angle and roll angle is obtained with the accelerometer readings or with an inclinometer. The initial yaw angle (azimuthal direction from East) is required to account for the Earth's rotation as will be demonstrated in section 4.1.

3.0 NUMERICAL PROCEDURE

The numerical procedure described in sections 3.1 and 3.2 has been implemented on the NRC IBM 3090 mainframe in double precision. Total execution time for a 90 second laboratory "manoeuvre" (40 Hz sampling rate) is approximately 35 CPU seconds. Although the procedure is iterative, no convergence problems were encountered.

3.1 RATE EQUATIONS

The complete equations expressing the relationship between rotation rate and attitude are taken from reference 1:

$$\dot{\psi} = \frac{r\cos\phi}{\cos\theta} + \frac{q\sin\phi}{\cos\theta} + \dot{L}\cos\psi\tan\theta$$
$$+ (\Omega_e + \dot{\lambda})(\sin L + \cos L\sin\psi\tan\theta) \qquad 3.1.1$$

$$\dot{\theta} = q\cos\phi - r\sin\phi - [\dot{L}\sin\psi - (\Omega_e + \lambda)\cos L\cos\psi] \qquad 3.1.2$$

$$\dot{\phi} = p + q\tan\theta\sin\phi + r\tan\theta\cos\phi + \left[\frac{\dot{L}\cos\psi}{\cos\theta} + (\Omega_e + \dot{\lambda})\cos L \frac{\sin\psi}{\cos\theta} \right] \quad 3.1.3$$

For this experiment, the rate of change in latitude and rate of change in longitude ($\dot{L}$ and $\dot{\lambda}$) are of course zero (flat Earth assumption), hence the equations can be simplified to:

$$\dot{\psi} = \frac{r\cos\phi}{\cos\theta} + \frac{q\sin\phi}{\cos\theta} + \Omega_e(\sin L + \cos L\sin\psi\tan\theta) \quad 3.1.4$$

$$\dot{\theta} = q\cos\phi - r\sin\phi + \Omega_e\cos L\cos\psi \quad 3.1.5$$

$$\dot{\phi} = p + q\tan\theta\sin\phi + r\tan\theta\cos\phi + \Omega_e\cos L \frac{\sin\psi}{\cos\theta} \quad 3.1.6$$

The Earth's rotation rate (relative to inertial space) is 15.04107 deg/hr, reference 2. When the Earth rate is accounted for, the azimuthal direction of the inertial module is required. The reference system is such that when the inertial module (or aircraft) is pointing East, ψ = 0.0 degrees. The sign convention is such that when the inertial module is facing North, ψ = -90.0 degrees (see figure 2).

When accounting for the rate gyroscope biases, the equations become:

$$\dot{\psi} = \frac{(r_m - b_r)\cos\phi}{\cos\theta} + \frac{(q_m - b_q)\sin\phi}{\cos\theta} + \Omega_e(\sin L + \cos L\sin\psi\tan\theta) \quad 3.1.7$$

$$\dot{\theta} = (q_m - b_q)\cos\phi - (r_m - b_r)\sin\phi + \Omega_e \cos L \cos\psi \qquad 3.1.8$$

$$\dot{\phi} = (p_m - b_p) + (q_m - b_q)\tan\theta\sin\phi + (r_m - b_r)\tan\theta\cos\phi + \Omega_e \cos L \frac{\sin\psi}{\cos\theta} \qquad 3.1.9$$

where L = 45.325509 degrees

These are the equations used in this study.

3.2 INTEGRATION AND SEARCH METHOD

In order to determine the biases, the above equations must be integrated from the start of the laboratory "manoeuvre" to the end. The pitch, roll and yaw angles at the end of the integration are compared to their values at the beginning. If the comparison does not result in the beginning and ending angles being the same for each of the three axes, the three rate gyroscope biases are appropriately adjusted to force agreement - an iterative procedure.

The initial pitch and roll angles used during the integration can be obtained from the accelerometer readings, as shown below. These angles are not required with high accuracy since they have minimal influence on the resulting biases. For example, the largest error in bias as a result of a 5 degree error in initial pitch angle was only 0.5 deg/hr (Q-gyro), as determined in a numerical experiment. This appealing insensitivity to initial conditions results from the fact that the numerical constraint is the change in angle (or lack thereof), not the absolute value.

$$\theta_o = \sin^{-1}\left(\frac{a_{x_o}}{g}\right) \qquad 3.2.1$$

$$\phi_o = \sin^{-1}\left(\frac{-a_{y_o}}{g\cos\theta_o}\right) \qquad 3.2.2$$

or:

$$\theta_o = \tan^{-1}\left(\frac{-a_{x_o}\cos\phi_o}{a_{z_o}}\right) \qquad 3.2.3$$

$$\phi_o = \tan^{-1}\left(\frac{a_{y_o}}{a_{z_o}}\right) \qquad 3.2.4$$

The inertial module remains stationary for the first 5 seconds of data recording, to allow average accelerometer readings to be calculated and used in the equations above. The error introduced by the accelerometer biases in the above equations will be small, since integration over time is not involved (i.e. a bias of 1 milli-g will produce an angular error of only 3.4 arc minutes). An inclinometer can also be used to determine the inertial modules initial pitch and roll angles. The initial yaw angle must be known since the Earth rate sensed by the individual rate gyroscopes is generally a function of azimuthal position. Since accounting for the Earth rate is considered a small correction for flight test purposes, a small error in the initial yaw angle is unimportant. A numerical experiment has shown that an error in initial yaw angle (Ψ_o) of 5 degrees results in a P-gyro bias error of only 2 deg/hr.

The integration method used in this study was a 5th and 6th order Runge-Kutta-Verner pair (DIVPRK of reference 3). The routine used to conduct the nonlinear search for the biases was a Levenberg-Marquardt algorithm (DNEQNF of reference 3). This algorithm routinely converged, even with initial bias estimates set to zero. A flowchart of the procedure is given in figure 3.

4.0 DISCUSSION OF RESULTS

A total of 21 separate "manoeuvres" were conducted on three separate days within a two week period. The experiments were conducted on separate days to check for turn-on to turn-on repeatability of the biases.

The first turn-on consisted of four "manoeuvres", the results of which are presented in figure 4. For each of the three rate gyroscopes, the computed biases are seen to be very repeatable.

The biases of flight test gyroscopes prior to flight are often estimated by simply recording data with the inertial module stationary. Ideally, the rate gyroscopes should read zero under these conditions (excluding the Earth rate - which is normal practice in flight testing), hence any non-zero reading is considered a bias. Note that for the UTIAS 12 bit A/D conversion (4096 counts) and ± 25 deg/sec range for each channel, the finest resolution achievable is 0.0122 deg/sec or 44 deg/hour. Hence, the biases can only be determined to a resolution of 44 deg/hour by using the above stationary module method. The method presented herein has essentially infinite resolution and the results presented in figure 4 are within the 44 deg/hour resolution of the stationary module method for all three gyroscopes. The results indicate that biases equivalent to 2 or 3 A/D conversion increments (counts) are present on all three channels. Three candidate sources of these relatively large biases are initial calibration error, rate gyroscope bias shift after calibration and A/D converter shift. The latter is considered to be the most probable.

The results from the second and third turn-ons are presented in figures 5 and 6, which are similar to the results from the first turn-on. The average biases for the three turn-ons are:

	TURN-ON 1 (deg/hr)	TURN-ON 2 (deg/hr)	TURN-ON 3 (deg/hr)
Q-rate gyro	-100.9	- 99.0	-101.2
P-rate gyro	- 79.9	- 75.6	- 77.4
R-rate gyro	-108.1	-107.6	-109.2

It is clear that the variation in bias from turn-on to turn-on, for a relatively short 2 week period, is minimal.

The results for all 21 "manoeuvres" are presented in figure 7. The overall averages and standard deviations for the three gyroscope biases are:

	AVERAGE (deg/hr)	STANDARD DEVIATION (deg/hr)
Q-rate gyro	-100.2	1.9
P-rate gyro	- 77.1	1.9
R-rate gyro	-108.3	2.6

A standard deviation of roughly 2 deg/hr (0.00055 deg/sec) is considered excellent, since the Earth rate (approximately 10.6 deg/hr at 45 degrees latitude) is rarely even considered for flight test purposes during standard calibrations. Results of this quality indicate that the initial assumptions are valid, that is, the biases are the dominant error sources and that they remain essentially constant for the duration of the manoeuvre. The results also demonstrate the stability (in the short term at least) of the UTIAS rate gyroscopes and data acquisition system.

To achieve results with 2 deg/hour standard deviation requires highly repeatable starting and ending points. Consider, for example, that if the true ending angle in pitch was different than the true starting angle by a 0.05 degree misplacement of the inertial module (3 arc minutes), this alone introduces an error of 2 deg/hour for a 90 second "manoeuvre". Hence, care must be exercised in the implementation of the method.

4.1 EFFECT OF EARTH RATE ON RESULTS

In order to demonstrate that the technique proposed herein was of sufficient accuracy to warrant the inclusion of the Earth rate in the calculations, a special test procedure was conducted during the third turn-on.

For the first two turn-ons, 13 "manoeuvres", the beginning and ending azimuthal positions were the same, ψ=-33.17 degrees, and the "manoeuvre" time histories were very similar. Each of the three gyroscopes sensed a different, but repeatable, component of Earth rate as shown below:

$$q = -\Omega_e \cos L \cos\psi \qquad 4.1.1$$

$$p = -\Omega_e \cos L \sin\psi \qquad 4.1.2$$

$$r = -\Omega_e \sin L \qquad 4.1.3$$

These are the components of Earth rate sensed by a stationary inertial module whose pitch and roll angles are zero. Note that azimuthal orientation affects the Q and P rate gyros and not the R gyro under these conditions. For a particular beginning and ending azimuthal orientation and similar "manoeuvre" time histories, the resulting biases would have been repeatable whether the Earth rate was included or not. Although repeatable, the results would be in error by the components of Earth rate not accounted for. Hence, the repeatability of the results from the first two turn-ons says little about the significance of including the Earth rate in the calculations. A special test was required for this.

During the experiments associated with the third turn-on, the starting and ending azimuthal positions for any one "manoeuvre" were identical as usual, however, they were changed by 90 degrees, from "manoeuvre" to "manoeuvre". This ensured that the gyroscopes sensed a different component of Earth rate for each "manoeuvre", thereby deliberately introducing an apparent randomness in the results if the Earth rate was not accounted for. Four of the eight "manoeuvres" during the third turn-on will be used for demonstration, and their starting and ending azimuthal positions are given in figure 8. As can be seen from figure 8, the four azimuthal positions cover the full 360 degree range in 90 degree increments.

Comparisons of each of the three calculated gyroscope biases for the above azimuthal orientations, both with and without the Earth rate accounted for, are given in figures 9, 10 and 11. It is clear from these figures, that the numerical procedure described herein is sensitive enough to warrant the inclusion of the Earth rate in the calculations. This is further demonstrated in the following table by the averages and standard deviations of the results shown in figures 9, 10 and 11, with and without the Earth rate accounted for.

	average with Ω_e (deg/hr)	average without Ω_e (deg/hr)	standard deviation with Ω_e (deg/hr)	standard deviation without Ω_e (deg/hr)
Q-rate gyro	-101.7	-101.6	1.7	10.5
P-rate gyro	- 77.6	- 77.8	0.9	8.1
R-rate gyro	-110.9	-121.5	1.7	1.7

Several interesting observations can be made about these results:

- Although the Q and P gyros sense a component of Earth rate that is a function of azimuth (see equations 4.1.1 and 4.1.2), the four manoeuvres cover the full 360 degrees in four 90 degree steps (figure 8), hence the resulting average bias over the four manoeuvres should be the same whether the Earth rate was accounted for or not. This is indeed the case for both the Q and P gyros as shown in the table above. The reason for this is that for two of the manoeuvres, components of Earth rate are being added and in the other two manoeuvres the same components are being subtracted.

- Although the averages for the Q and P gyros should be the same, the standard deviations should not. Clearly, the standard deviations for the calculations without the Earth rate accounted for are much larger for the Q and P gyros, and this alone warrants the inclusion of the Earth rate in the calculations.

- As shown by equation 4.1.3, the R gyro Earth rate component should be 15.04cos45.32 = 10.6 deg/hour. The above table shows that the numerical procedure's four manoeuvre average agrees (121.5 - 110.9 = 10.6 deg/hour). This is a very clear demonstration of the sensitivity of the numerical procedure, since agreement with the truth to a tenth of a degree per hour has been achieved.

- Since the component of Earth rate sensed by the R gyro is not sensitive to azimuth (equation 4.1.3), the standard deviation should be the same whether the Earth rate is accounted for or not. The above table shows this to be the case. This explains why, in figure 11, that although the absolute value of bias is different when including or excluding the Earth rate, the variability in the results is the same for both cases. This is not true, nor should it be, for the Q and P gyros since they are sensitive to azimuthal orientation.

It should be clear from the foregoing that the search algorithm is indeed determining the correct gyroscope (or gyroscope channel) biases, and not arbitrary numbers which happen to satisfy the constraints.

5.0 CONCLUSION

A numerical technique has been presented for quickly estimating rate gyroscope biases. The accuracy of the method has been shown to be superior to conventional flight test calibration procedures, without requiring any calibration hardware whatsoever. Furthermore, the method is relatively insensitive to initial conditions (θ_o, ϕ_o, ψ_o), thereby allowing the user to forego accurate initial measurements. In addition, the technique requires only a few moments of time to complete and is suitable for use within a stationary aircraft prior to takeoff, thereby providing up to date bias estimates for each flight test.

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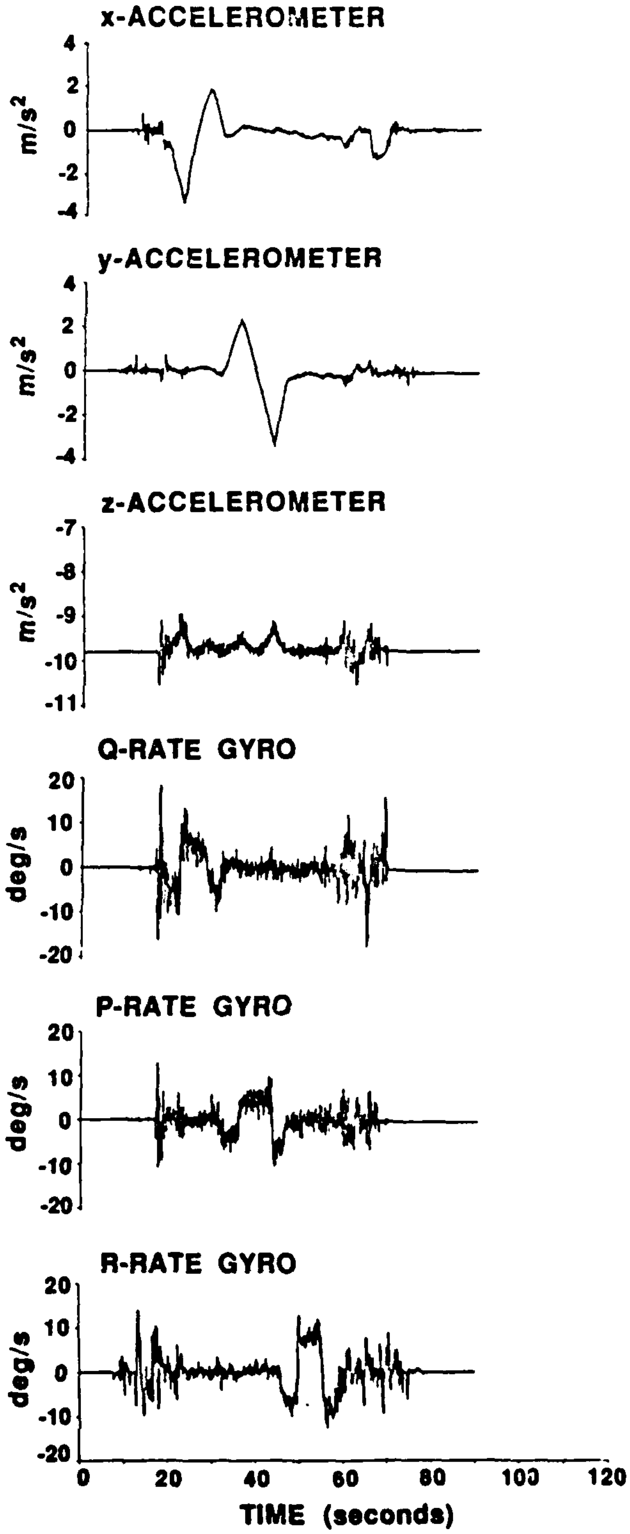


FIG. 1: SAMPLE LABORATORY MANOEUVRE TIME HISTORIES

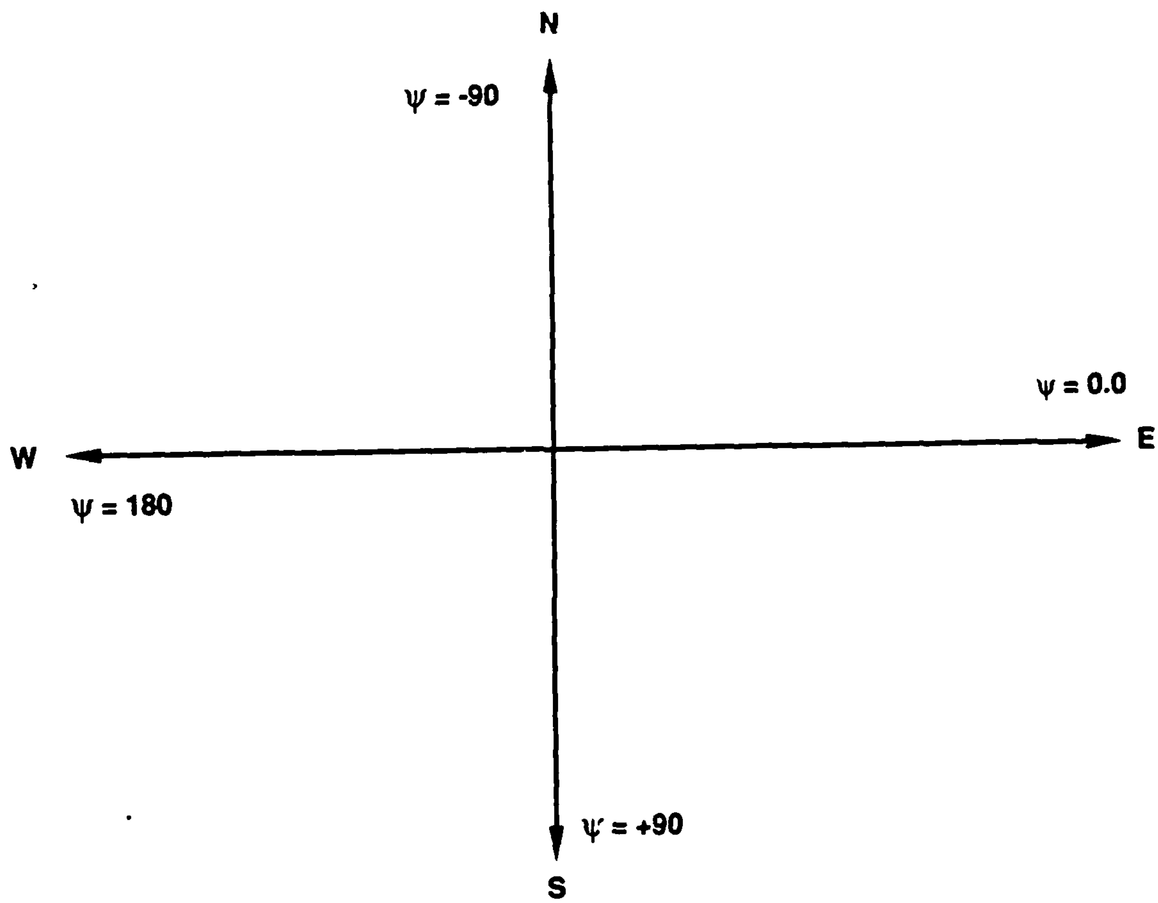


FIG. 2: AZIMUTHAL REFERENCE SYSTEM

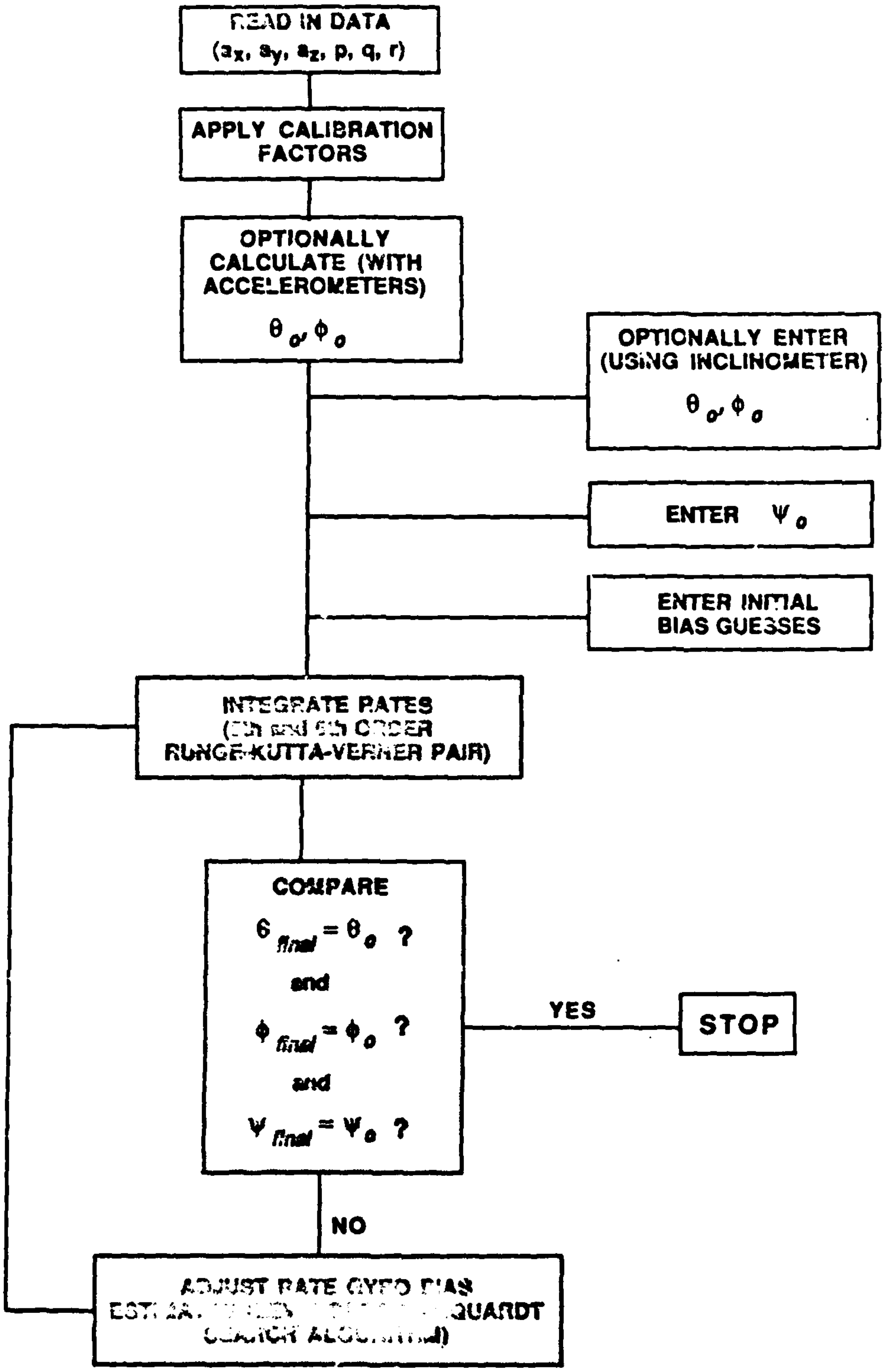
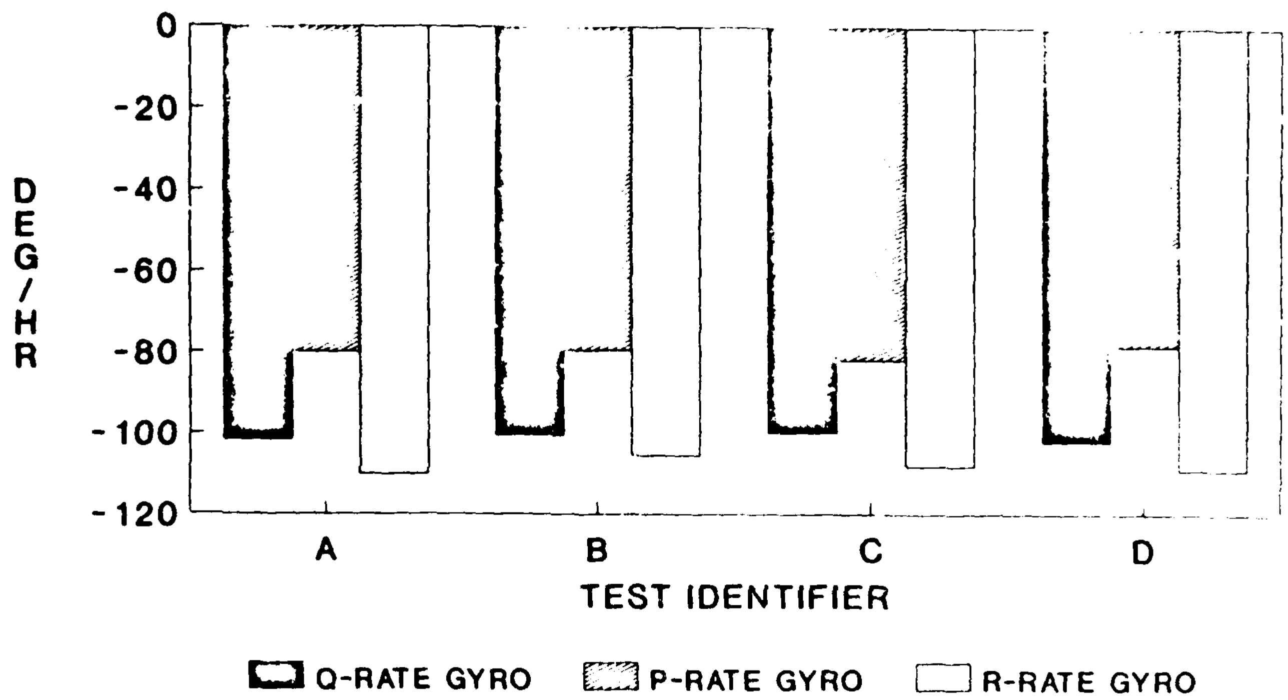
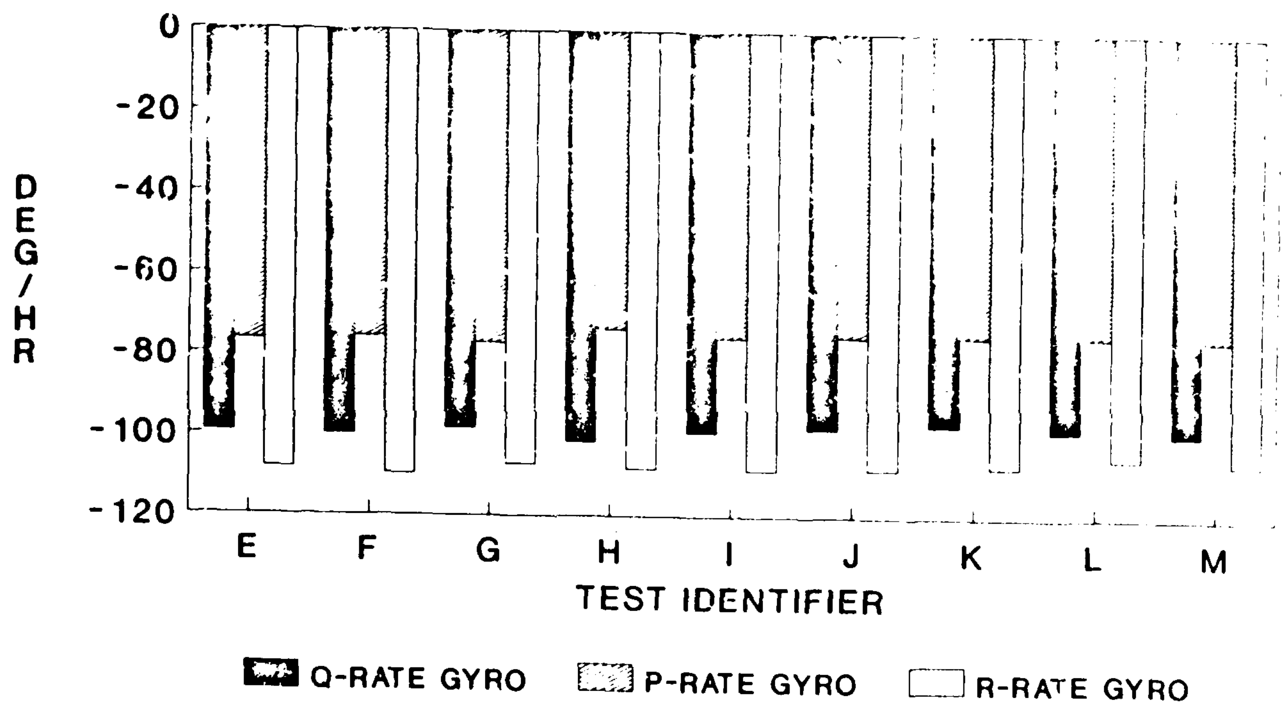


FIG. 3: NUMERICAL PROCEDURE FLOWCHART



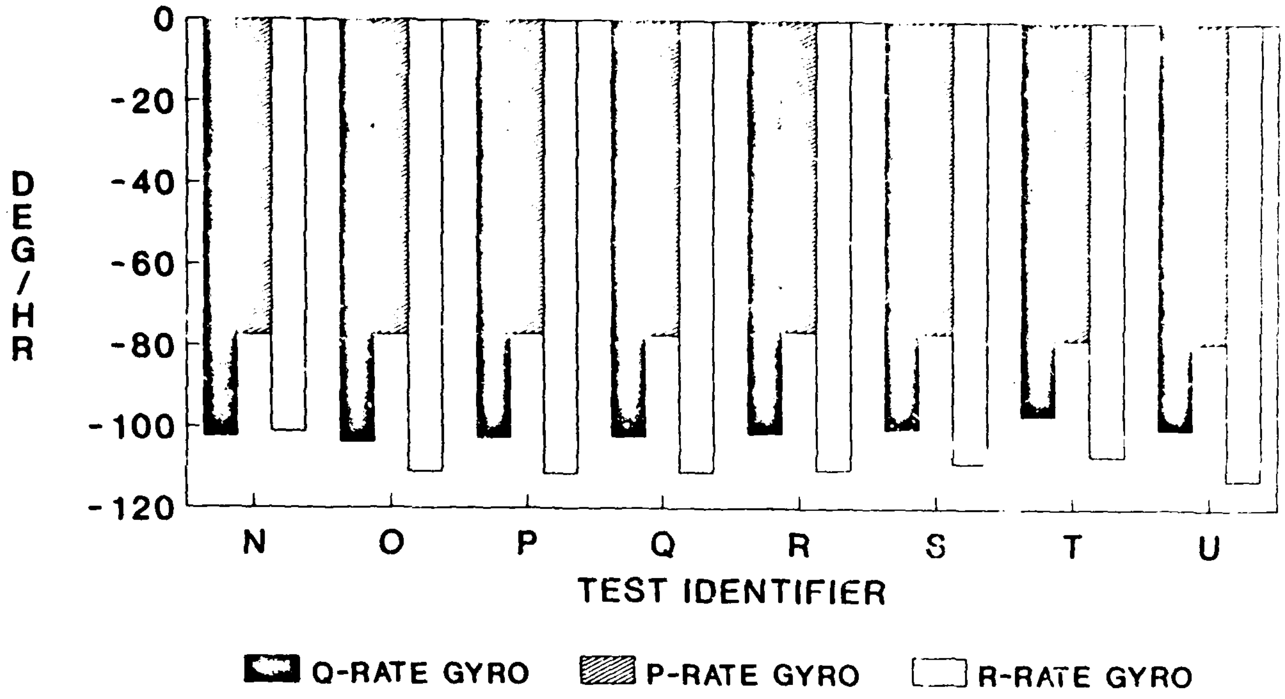
Q-average = -100.9
P-average = - 79.9
R-average = -108.1

FIG. 4: COMPUTED GYROSCOPE BIASES FOR TURN-ON #1



Q-average = - 99.0
P-average = - 75.5
R-average = -107.6

FIG. 5: COMPUTED GYROSCOPE BIASES FOR TURN-ON #2



Q-average = -101.2
P-average = - 77.4
R-average = -109.2

FIG. 6: COMPUTED GYROSCOPE BIASES FOR TURN-ON #3

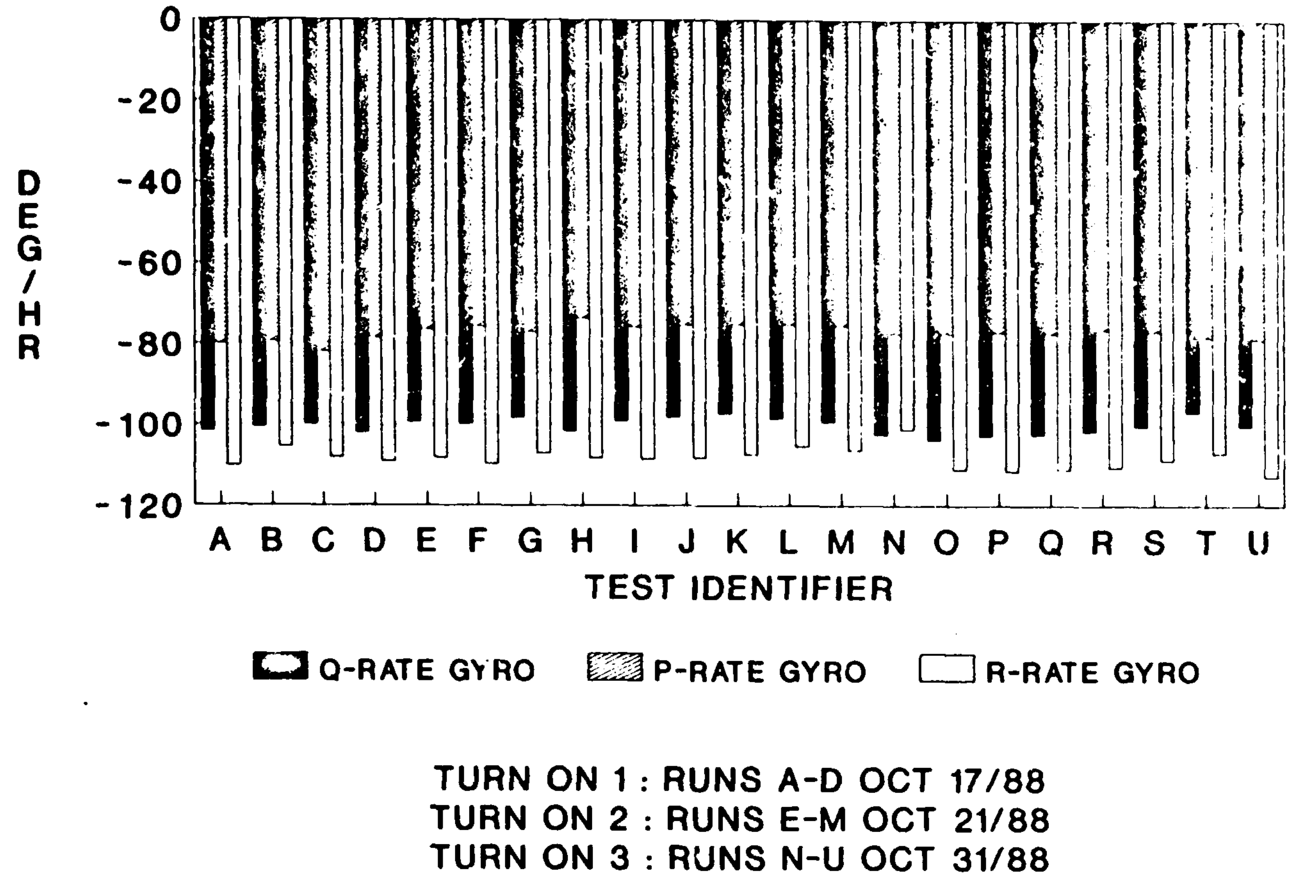


FIG. 7: COMPUTED GYROSCOPE BIASES FOR ALL TURN-ONS

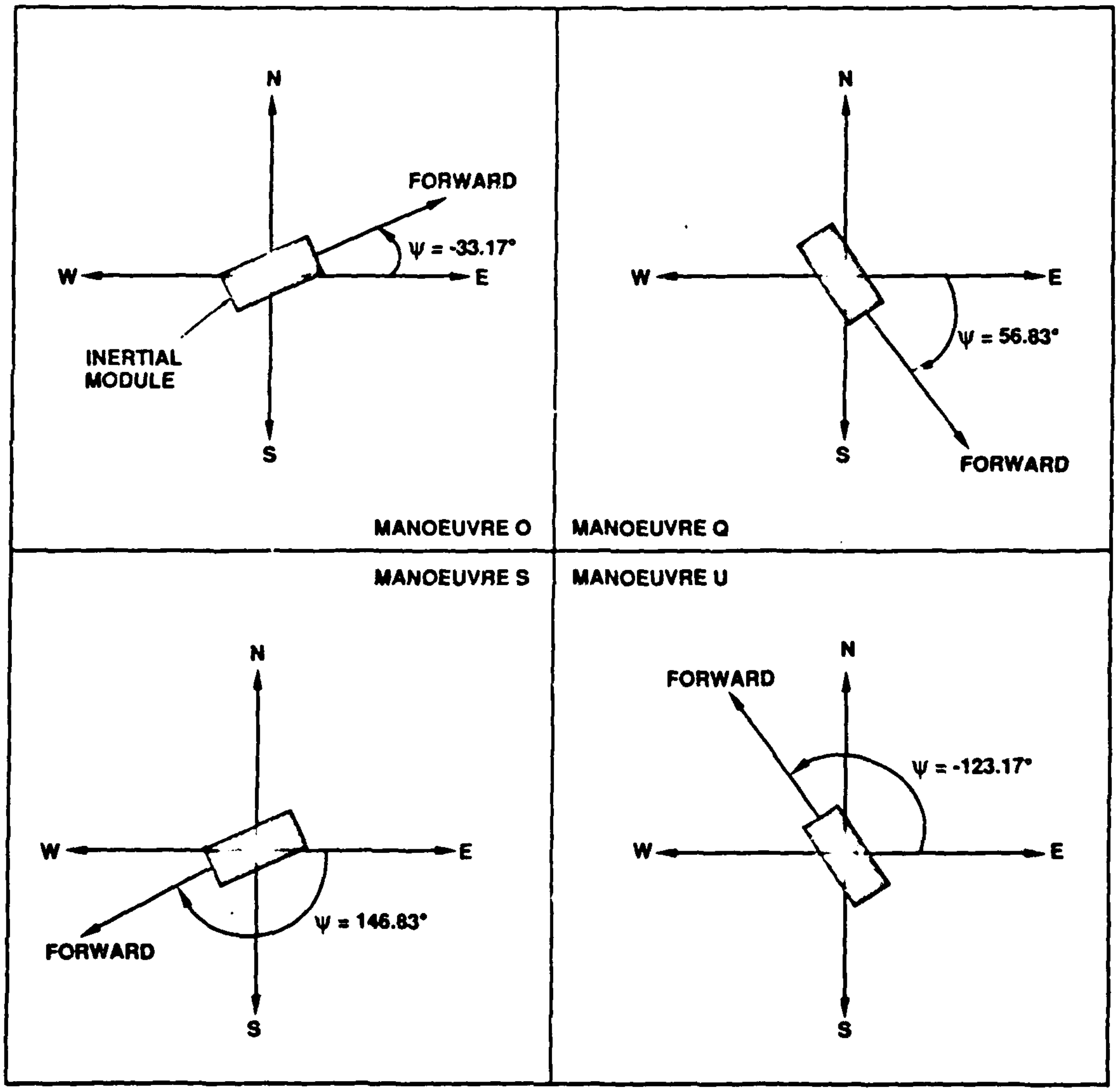


FIG. 8: AZIMUTHAL ORIENTATIONS FOR TURN-ON #3

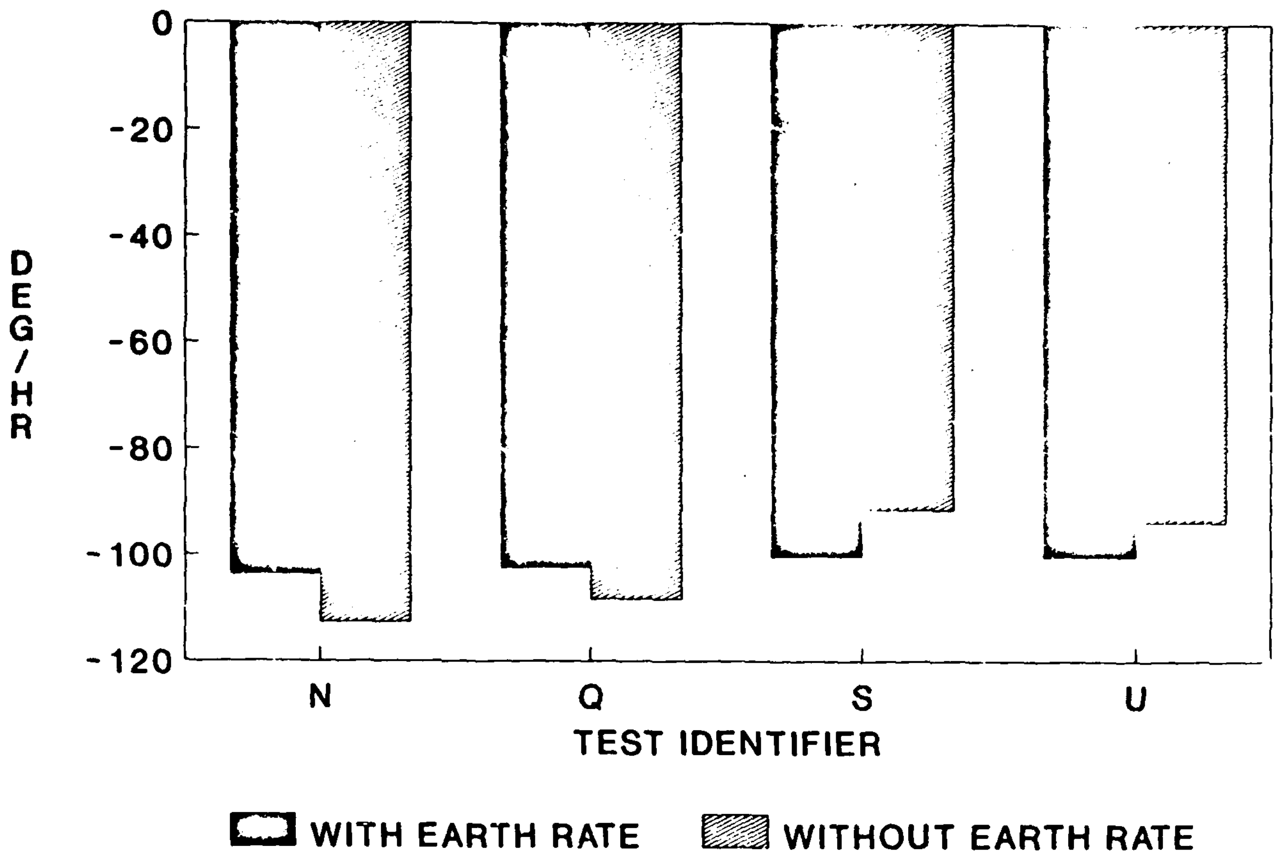


FIG. 9: EFFECT OF EARTH RATE ON Q-GYRO BIAS

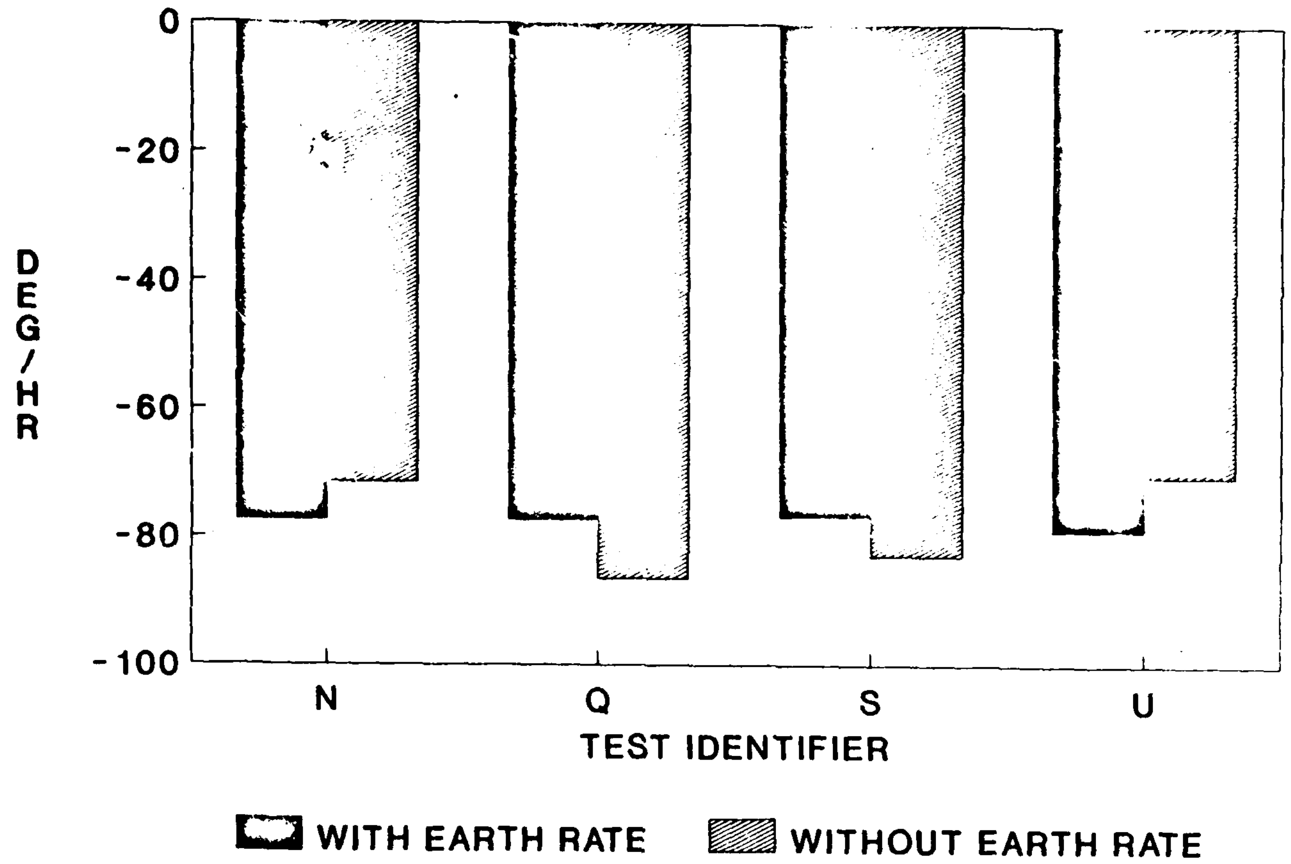


FIG. 10: EFFECT OF EARTH RATE ON P-GYRO BIAS

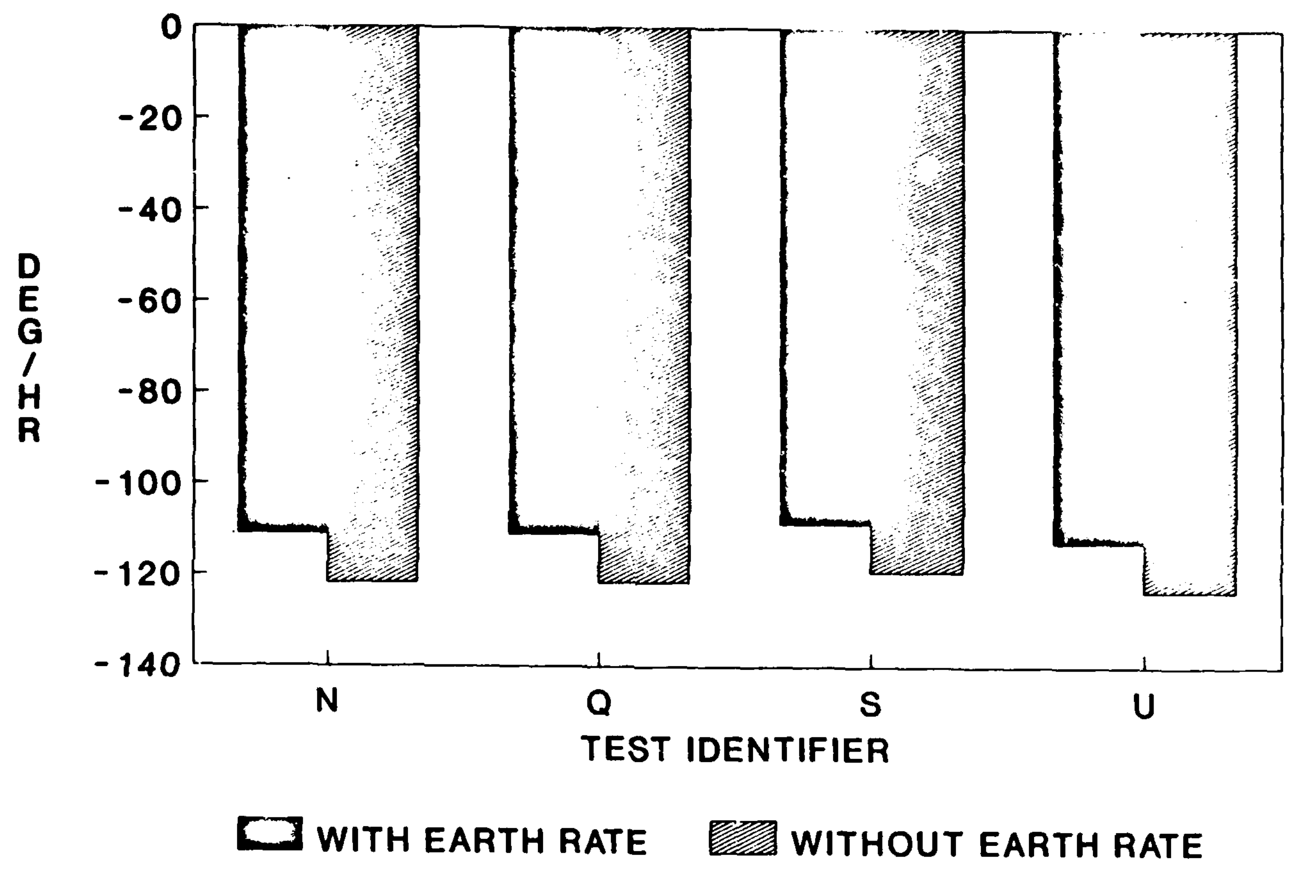


FIG. 11: EFFECT OF EARTH RATE ON R-GYRO BIAS

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DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Flight paths — reconstruction
2. Flight test. — gyroscopic
3. Gyroscope — flight testing

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SUMMARY/SOMMAIRE

Rate gyroscope biases play an important role in flight tests requiring flight path reconstruction, a method often used in aircraft parameter estimation. The biases can drift with time, be affected by system power up and, ideally, should be calibrated before each flight to maintain optimum performance. This report details a numerical method to determine the biases of high quality flight test rate gyroscopes immediately prior to a flight. The accuracy of the method is such that the earth rate is clearly sensed and accounted for, a variable rarely considered in flight testing. The method requires minimal time and no calibration hardware.

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